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Uptake and toxicity of lead and other elements

Uptake and Toxicity of Lead and other Elements by Lettuce and Beet Grown on Soil Contaminated by Emissions from a Secondary Lead Smelter

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Abstract. A study was conducted in 1987 in the greenhouse and field to investigate the uptake of lead and other elements by lettuce and beet grown on soil which had been contaminated by emissions from a secondary lead smelter. The concentrations of lead in each of the four soil treatments were approximately 15 (control); 1000; 1500 and 3000 ug/g lead. Results of the greenhouse findings were generally in line with those of the field. In general, the chemical contents of lettuce and beet from the smelter soils were higher than lettuce and beet from the control soil. The concentrations of Pb and other elements were higher in lettuce roots than tops; conversely, the concentrations of these same elements were greater in beet tops than roots. In most cases, the concentrations of Pb, As, Cd, Zn and Cu in plant tissues increased with each increment of soil contamination. The lead values in lettuce and beet showed a significant correlation with lead and other elements in the soil.

Introduction

Contamination of soil and vegetation by lead, arsenic and other elements has been reported in the vicinity of several secondary lead smelters in Toronto, Ontario (Roberts _et al_. 1975; Linzon _et al_. 1976; Temple _et al_. 1977). Lead concentrations in excess of 20,000 ug/g have been found in surface soil near one smelter and soil concentrations exceeding 500 ug/g lead were found over 3 km downwind (Linzon _et al_. 1976; Rinne _et al_. 1986). The generally accepted range of concentrations for most unpolluted soils is 2 to 200 ug/g lead (Swaine 1955). A large number of vegetable crops are known to accumulate lead through uptake resulting in toxicity and growth effects (Motto _et al_. 1970; John and Van Laerhoven 1972; Cox and Rains 1972; Baumhardt and Welch 1972; Page and Gange 1972; Beavington 1975; Preer _et al_. 1980; Hibben and Hager 1984). Many homeowners near the lead smelters have raised concerns regarding the consumption of crops harvested from their gardens on the basis of possible heavy metal contamination. In an effort to learn more about the potential for contamination of edible crops, this study was initiated to investigate the uptake of lead and other elements and their effects on the growth and yield of lettuce and beet in the greenhouse and field.

Materials and Methods

Soils

The experiment was conducted at the Ontario Ministry of the Environment Controlled Environment Laboratory in Brampton, about 40 km NW of Metropolitan Toronto. The lead rich sandy loam soil used in this study was obtained from an area about 0.5 m E and downwind from a lead smelter in Toronto. A similar soil but with low lead content was obtained from an area outside the influence of the emission source. The two soils were transported to the Brampton facility. The lead rich soil was mixed with control soil in separate batches to reflect 3000, 1500, 1000 and 15 (control) ug/g lead concentrations, typical of the pattern of decreasing contamination found found for lead and other elements with increasing distance from the smelter. Head lettuce and table beet were chosen for this study because preliminary analysis of collected samples revealed high concentrations of lead present in the tissues of these species.

Greenhouse Experiment

In the greenhouse, seeds of lettuce, <u>Lactuca</u> <u>sativa</u> cv. Ithaca and beet, <u>Beta vulgaris</u> cv. King Red were planted in control sandy-loam soil and transplanted (6-7 wk old) in mid-January 1987 singly into 15-cm pots containing prepared soil with one of four different lead concentrations. All plants received applications of soluble fertilizer equivalent to 1 kg/400 l water of 20:20:20 which was applied in two equal amounts, at transplanting, and again 6 wk after transplanting. Plants were kept in the greenhouse throughout the experiment and were grown in natural daylight supplemented with fluorescent and incandescent lamps using a 14 h photoperiod at 20-22 C. There were six replicates for each of lettuce and beet.

Field Experiment

Outside the greenhouse in an excavated area, the prepared test soils were placed in individual plots of 1.2 x 4.3 m for each soil. Corrugated plastic sheets turned on edge and buried 40 cm were used to separate each of the four soils from each other and from the adjacent soil outside the plot. Also, between each sub-plot was a 0.6 m soil pathway. The soils within plots were homogenized and the initial chemical content and pH were determined for each. Methods for the sampling and processing of soils and chemical analysis are described elsewhere (Bisessar 1989). Soil pH (measured range of 7.7 to 6.8) was determined in a suspension of soil in distilled water (1:1,w/v) with a Corning pH meter. Lettuce (cv.Ithaca) and beet (cv. King Red) seedlings at 6-7 wk old were transplanted to the field plot in mid-June, 1987. Lettuce was transplanted in a single row in each sub-plot and spaced 30 cm apart in the row. Beet was

spaced 10 cm in a single row parallel to the lettuce in each sub-plot. All plants received applications of fertilizer equivalent to 240 kg/ha of 20:20:20 which was applied in two equal amounts, at transplanting, and again at 5 wk after transplanting. The plot was prepared and planted according to standard commercial practices and irrigated when necessary. Weeds were removed manually.

Bags of sphagnum moss were set up at the plot site as well as in the greenhouse for trapping and retaining lead and other air pollutants (Temple et al. 1981). The bags were attached to a plastic supporting bracket and mounted at plant height and at 2 m above ground level on a wooden pole in the centre of the plot or the greenhouse bench. After 30 days of exposure, the bags were removed and the moss was processed and analysed for heavy metals, primarily lead, in the same manner employed for vegetation.

The plants were harvested at maturity in mid-March from the greenhouse and in mid-August from the field. Six plants were chosen at random from each treatment in the greenhouse and five plants were chosen from each row of the four sub-plots in the field for yield determination. Individual plants were cut into shoot (above ground) and root (below ground) portions. Shoots and roots were washed individually in tap-water, blotted dry, and the oven-dry weight was determined. The mean dry shoot and root weights were calculated. Chemical analysis was performed on separate oven-dried shoot and root samples. Samples of surface soil (0-15 cm) were collected from each treatment in 6 and 5 replicates from the greenhouse and field, respectively for chemical analysis. Soil samples were air-dried for 48 hr, sieved through a 45-mesh screen, stored in screw-capped glass jars prior to chemical analysis.

Lead, Cd, Cu and Zn contents of vegetation and soil were determined by conventional atomic absorption spectrophotometry (AAS) whereas As contents were determined by the hydride method using flameless atomic absorption spectrophotometry (Vijan and Wood 1974). Ammonium acetate-extractable Pb was determined at harvest time from the field soils only. This was done by shaking 5-g of air-dried soil (sieved through a 355 um aperture sieve) with 25 ml 1 N ammonium acetate (pH 7) for 2 h, centrifuging and analysing the supernatant by atomic absorption spectrophotometry.

Soil and plant chemical analysis results and yield data were subjected to statistical evaluation including analysis of variance and Duncan's multiple range test.

Results and Discussion

Chemical concentrations in soils

The concentrations of various chemical elements in soils at harvest are shown (Table 1) and followed the sequence: Pb> Zn> Cu> As> Cd> in both the greenhouse and field studies. There were significant ($p<0.05$) differences between the control and the smelter soil treatments in the greenhouse and field, confirming the targeted concentrations that had been selected (Table 1).

The concentrations of all elements in the soils were within the range of background levels in agricultural soils in Ontario except for Pb and Zn. A recent survey of agricultural soils in Ontario indicated Pb levels ranging from 1.5 to 888, Cd levels from 0.10 to 8.1, As levels from 1.1 to 91.6, Cu levels from 2.1 to 144 and Zn levels from 4.6 to 162, all in ug/g dry weight (Frank et al. 1976). Zinc values in the metal soil in this study ranged from 32 to 290 ug/g and were considered to have no adverse effect on plants. Moreover, sewage sludge amendments containing Zn at 1070 or 2920 ug/g added to soils and used for uptake studies showed no adverse effect on lettuce plant growth (Dowdy & Larson 1975 ; Zwarich & Mills 1982).

The mean extractable-Pb concentration increased significantly ($p<0.05$) with each increment of smelter soil treatment in the field (Table 1). There was a significant correlation ($r= 0.98$) between the mean extractable-Pb and total Pb (Table 1). Extractable Pb measurement was not carried out with the greenhouse study.

Monthly moss bag analysis of air borne Pb monitored in the greenhouse and field ranged from 20 to 27 ug/g and 52 to 82 ug/g, respectively. The concentrations of Pb found at plant height and about 2 m above were not elevated. This suggests that the amounts of Pb contributed by current deposition were insignificant in relation to historical soil contamination (Table 1).

Chemical concentrations in vegetation

Lettuce

The concentrations of the various elements in lettuce harvested from the greenhouse and field are shown (Table 2). The chemical contents of Pb, Cd, As, Cu and Zn in lettuce root and foliage from the smelter soils were significantly higher ($p<0.05$) than in lettuce from the control soil, indicating that considerable uptake from the smelter soil had occurred both in the greenhouse and field (Table 2). Lead was quantitatively the greatest pollutant among the elements and the concentration in lettuce from the greenhouse and field increased with each increment of smelter soil treatment. The effects of the Pb

treatment were most prominent in the roots but also showed up to a lesser extent in the leaves, indicating absorption of Pb by the roots and some translocation to the leaves (Table 2).

The edible portion of lettuce contained lower concentrations of Pb than roots. These results were in accord with those of Miller & Koeppe (1972); Hutchinson et al.(1974) and Czuba & Hutchinson (1980). In the present study, Pb levels found in the edible portion of lettuce ranged from 4 to 314 ug/g dry weight (Table 2). Higher Pb values were reported for edible lettuce leaves in the vicinity of old lead smelters (Roberts et al. 1975). The highest Pb concentrations were recorded in lettuce, which agrees with studies where it has been shown that this plant species takes up Pb much more efficiently than other plant species (Motto et al. 1970). The Pb levels in plants have normally been reported to be < 5 ug/g (Motto et al. 1970) and 0.1 to 0.4 ug/g (Patterson 1965). The Pb levels reported for lettuce from the greenhouse and field studies were considerably higher than the highest levels reported for crops grown in orchards (Chapman 1966). The elevated Pb levels found in lettuce, particularly in the roots, could be attributed in part to surface contamination that was not removed by the washing technique.

Cadmium levels were significantly higher ($p<0.05$) in lettuce from the metal rich soil compared to Cd in lettuce from the control soil (Table 2). Generally, higher levels of cadmium were found in lettuce roots compared to the foliage. This was in accord with the findings of other investigators (John and Van Laerhoven 1976). The Cd levels were generally the highest in the non-consumable portion of lettuce which ranged from 0.42 to 7 ug/g compared to the consumable portion which ranged from 0.5 to 3 ug/g, all dry weight (Table 2). Cadmium levels of the same magnitude were obtained in lettuce grown in sewage sludge-amended soils (Dowdy & Larson 1975; Zwarich & Mills 1982).

In the greenhouse, As levels generally were significantly higher ($p <0.05$) in lettuce from the metal-rich soil compared to lettuce from the control soil (Table 2). Arsenic levels in the non-consumable portion of lettuce from the greenhouse and field ranged from 0.62 to 34 ug/g and were consistently higher than the levels from the consumable portion which ranged from 0.4 to 3.40 ug/g, all dry weight (Table 2). As the case with Pb and Cd, As concentrations were higher in lettuce roots compared to foliage, both in the greenhouse and field. The lower concentrations of As found in edible portions is in agreement with the concentrations found in lettuce grown on sprayed orchard soils (Jones and Hatch 1945).

Copper uptake in lettuce tissues from the smelter soils was significantly higher ($p <0.05$) than from the control soil (Table 2). In general, Cu uptake in lettuce increased with increasing rate of smelter soil treatment (Table 2). The concentrations of Cu in lettuce roots greatly exceeded those found in lettuce foliage, indicating the relative immobility of root- absorbed Cu. Copper concentrations in the non-consumable portion of lettuce ranged from 17 to 138

ug/g while those in the consumable portion ranged from 11 to 41 ug/g. The maximum tissue concentration of 41 ug/g Cu in the edible portion of lettuce was within the range of 7 to 44 ug/g reported for background Cu concentration in lettuce cultivars (Lindsay 1979). Copper, unlike, Pb, Cd and As is an essential plant nutrient, and in general, plants do not accumulate Cu to levels that are likely to be toxic to animals or humans.

Zinc concentrations, like Cu, in lettuce from the smelter soil were significantly higher ($p < 0.05$) than those from the control soil (Table 2). The concentration of Zn in lettuce roots exceeded that found in lettuce foliage, particularly in the greenhouse study, indicating the relative immobility of root-absorbed Zn (Table 2). Similar results were reported for lettuce grown on sludge-amended soils (Dowdy and Larson 1975; Zwarich and Mills 1982). Zn concentrations in lettuce roots ranged from 35 to 143 ug/g and in the edible foliage from 28 to 83 ug/g, all dry weight (Table 2). The maximum concentration of 83 ug/g in the edible portion of lettuce was within the range of 34 to 340 ug/g reported for non-toxic background concentrations for lettuce cultivars (Lindsay 1979). Zinc, like Cu, is an essential nutrient, and increased dietary levels may often be benefical (Allaway 1968).

Beet

Concentrations of the various elements analysed in beet from the greenhouse and field are shown in Table 3. Generally, the levels of Pb, Cd, As, Cu and Zn in beet grown on smelter soil were significantly higher ($p < 0.05$) than beet grown on the control soil both in the greenhouse and field. The As concentrations in beet root from the field were not detectable (Table 3). The results of these studies clearly show Pb, Cd, Cu and Zn were readily accumulated in beet grown on the metal rich soil. The total amount of Pb and other elements in beet root plus foliage increased with increasing soil contamination. Lead and other elements were translocated to and accumulated in the foliage at a higher concentration than in the roots (Table 3). In contrast to lettuce root in this study, which contained the highest Pb as well as high concentrations of the other elements, the root portion of beet contained the least amount of Pb. Similar findings were reported for metals in radish and carrot (John 1972; Dowdy and Larson 1975). The relationship between soil Pb and Pb in lettuce and beet foliage (F) and beet root (R) for the combined treatments from the greenhouse and field study are shown in Figure 1.

The concentrations of Pb and other metals were consistently higher in lettuce tissues than in corresponding beet tissues, suggesting that lettuce has a greater affinity for Pb and other metals. This is consistent with other reports (Dowdy & Larson 1975). Where a toxic element was found to be elevated in a beet sample from a smelter soil treatment, other toxic elements in that sample also were elevated. A similar pattern has been observed by other investigators (Beavington 1975). The concentrations of metals in beet tissues followed the

sequence : Zn > Pb > Cu > Cd > As. In the case of lettuce, the sequence was Pb > Zn > Cu > As > Cd both in the greenhouse and the field study.

Copper and Zn, unlike the Pb, Cd, and As are essential elements necessary for plant growth. Copper was taken up by beet in almost equal amounts by both root and foliage (Table 3). Copper concentrations in beet tissues ranged from 4 to 17 ug/g and were within the normal range of 5 to 20 ug/g. The highest concentration of 17 ug/g Cu in beet is not likely to be toxic and has been considered normal for plant tissues (Allaway 1968).

Zinc, like Cu, also was taken up and translocated within the beet plant and the total Zn concentrations were higher in beet foliage compared to the root in the more contaminated soils (Table 3). Zinc concentrations in beet tissues ranged from 24 to 125 ug/g in this study and were within the range reported for vegetables grown on sludge-amended soils (Dowdy & Larson 1975; Zwarich & Mills 1982). Zinc levels reported were within non-toxic background levels for vegetables (Lindsay 1979).

Effects on yield

The mean dry weights of lettuce and beet (root and foliage) from the greenhouse and field are shown in Table 4. There were significant differences ($p < 0.05$) in lettuce and beet mean weights between the control soil and the smelter soil treatments with the latter generally showing the lowest weights (Table 4). Generally the mean weights of lettuce and beet grown in the smelter soil were lower than the control soils but were not significant except for beet root weights from the field (Table 4). Growth reductions have also been reported for Pb in plants (Miller and Koeppe 1970; Miller et al. 1977). Also slight growth increases were observed in lettuce and beet foliage from soils with 500 and 1000 ug/g Pb. Growth increases or stimulations due to Pb in soil have previously been reported (Wallace & Romney 1970; Baumhardt and Welch 1972). There were consistent decreases in the mean weight of lettuce and beet on smelter soil treatment containing 1500 ug/g Pb or higher but at the same time no definite foliar toxicity symptoms were observed. However, lettuce and beet did not develop normally and appeared dwarfed or stunted at the highest Pb concentrations.

Conclusions

Lead and other trace elements were taken up by roots and translocated to above ground portions of plants grown in contaminated smelter soils. Results of uptake and translocation of Pb and other metals in lettuce and beet from the greenhouse study varied in magnitude but were consistent with those of the field study.

The concentrations of Pb and other metals in lettuce and beet tissues increased sharply as the Pb and other metal concentrations increased in the soils. The edible foliage of lettuce consistently contained higher concentrations of Pb and other elements than edible foliage or roots of beet.

The highest Pb concentrations of 3000-3500 ug/g in smelter soils did not induce visible foliar injury symptoms but were effective in depressing growth and yields of lettuce and beet.

Based on this study, the elevated Pb, Cd and As concentrations found in the edible tissues of lettuce and beet corroborate the homeowners' concerns about the contamination of produce raised on contaminated soil near lead smelters, and support the clean-up activities that were undertaken to remove contaminated soils from residential and publicly accessible areas.

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Table 1. Some chemical components of the soils in the greenhouse and field on a dry weight basis (ug/g)

Soil	Pb	Cd	As	Cu	Zn	Extractable Pb (ug/g)
GREENHOUSE						
1 (control)	54 a	0.4 a	6 a	19 a	55 a	-
11	501 b	0.8 b	9 b	27 b	60 b	-
111	1566 c	2.0 c	16 c	64 c	139 c	-
1V	3483 d	3.0 d	35 d	152 d	290 d	-
FIELD						
1 (control)	16 a	<0.2 a	3 a	10 a	32 a	<2 a
11	923 b	0.9 b	16 b	43 b	101 b	22 b
111	1440 c	1.1 b	13 b	52 b	122 b	54 c
1V	3140 d	2.9 c	32 c	115 c	246 c	158 d

In each column, values shown are arithmetic mean of 6 and 5 replicates respectively in the greenhouse and field investigations.

Values followed by the same letter do not differ significantly at $p<0.05$) according to Duncan's multiple range test.

Table 2. Concentrations of various elements in lettuce from the greenhouse and field at harvest, ug/g dry weight.

Treatment	Root					Foliage				
Soil Pb(ug/g)	Pb	Cd	As	Cu	Zn	Pb	Cd	As	Cu	Zn
GREENHOUSE										
54(control)	32 a	1.2 a	5 a	51 a	55 a	5 a	1 a	0.4 a	21 a	28 a
501	698 b	3.0 b	11 b	63 b	82 b	35 b	2 b	0.7 b	20 a	56 b
1566	1517 c	6.0 c	30 c	118 c	140 c	103 c	3 c	1.0 c	22 a	79 c
3483	1983 c	7.0 c	34 c	138 d	143 c	162 d	3 c	2.0 d	25 b	79 c
FIELD										
16(control)	10 a	0.42 a	0.62 a	17 a	35 a	4 a	0.5 a	0.51 a	11 a	34 a
923	131 b	1.48 b	2.34 a	24 b	53 b	92 b	1.4 b	1.72 ab	18 a	58 b
1440	171 b	1.60 b	2.05 a	35 b	66 c	144 b	1.8 bc	2.80 b	22 a	58 b
3140	323 b	2.78 c	5.12 b	66 c	80 d	314 c	2.2 c	3.40 b	41 b	83 c

Values within greenhouse and field followed by the same letter do not differ significantly at p<0.05) according to Duncan's multiple range test.

Table 3. Concentrations of various chemical elements in beet from the greenhouse and field at harvest, (ug/g dry weight.

Treatment Soil Pb(ug/g)	Root					Foliage				
	Pb	Cd	As	Cu	Zn	Pb	Cd	As	Cu	Zn
GREENHOUSE										
54 (control)	6 a	0.1 a	0.25 a	13 ab	41 a	6 a	0.3 a	0.2 a	13 a	24 a
501	10 ab	0.3 b	0.31 b	10 a	37 a	26 b	1.0 a	0.4 a	14 ab	37 b
1566	27 bc	0.9 c	0.56 bc	11 a	53 b	34 b	3.0 b	0.5 ab	16 b	87 c
3483	29 c	2.0 d	1.10 c	15 c	77 c	39 c	4.0 b	0.6 b	17 b	125 d
FIELD										
16 54 (control)	1 a	0.4 a	<0.3	6 b	24 a	<1 a	0.34 a	<0.3 a	6 a	21 a
923	5 b	0.3 a	<0.3	7 b	31 b	15 b	0.62 a	0.4 b	7 b	27 a
1440	8 c	0.6 ab	<0.3	4 a	28 ab	19 b	2.00 b	0.3 b	5 a	42 b
3140	15 d	0.8 b	<0.3	6 b	47 c	47 c	3.20 c	0.7 c	7 b	62 b

In each column, values within greenhouse and field followed by the same letter do not differ significantly at $p<0.05$ according to Duncan's multiple range test.

Values with no letter following are not significantly different.

Table 4. Dry weight of lettuce and beet from the greenhouse and field at harvest (g)

Treatment Soil Pb (ug/g)	Lettuce		Beet	
	Root	Foliage	Root	Foliage
GREENHOUSE				
54 (control)	6 b	9 ab	6	3 a
501	3 a	10 b	5	6 b
1566	3 a	8 ab	5	4 ab
3483	3 a	6 a	4	4 ab
FIELD				
16 (control)	12 b	8 b	21 c	28 c
923	14 b	11 c	25 d	32 c
1440	10 a	8 b	18 b	22 b
3140	9 a	6 a	10 a	15 a

In each column, values within the greenhouse and field followed by the same letter do not differ significantly at $p < 0.05$ according to Duncan's multiple range test.
Values with no letter following are not significantly different.

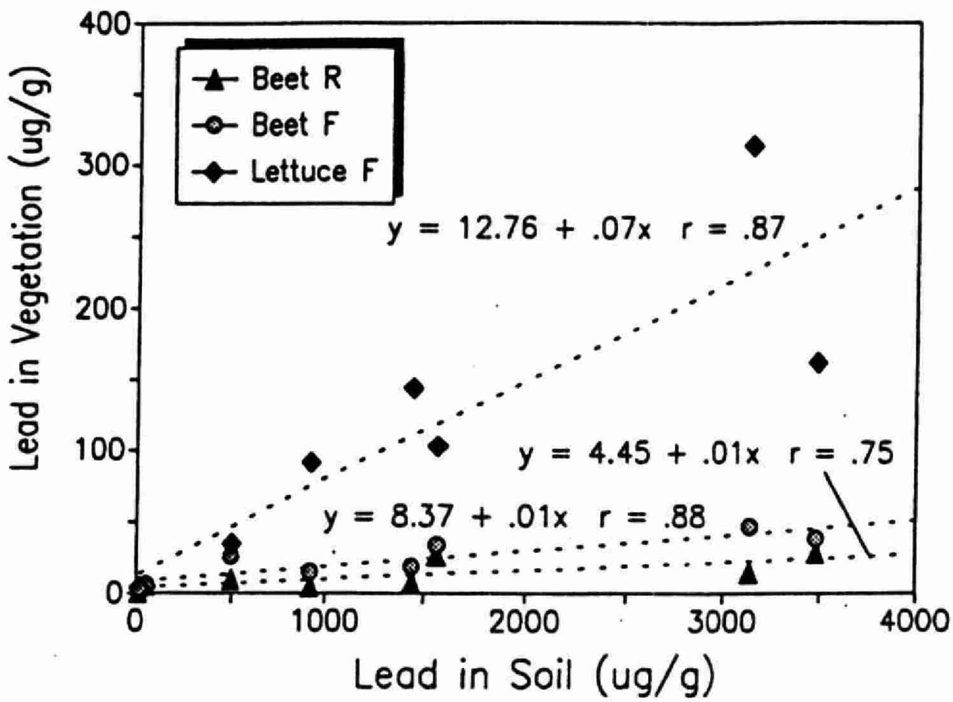

Fig. 1 Relationship between soil and plant lead levels

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